The Lives of Stars

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The Rundown

Stars in a Nutshell *(30 min)* — Lecture

→ **Finding the Main Sequence** *(30 min)* — Lecture, Working on BGSC2

→ **Stellar Lifetimes** *(15 min)* — Working on BGSC2

Key

- Lecture
- Working on BGSC2

Slides with a Blue background: computing challenge

`Fixed-width` text with this background indicates commands you should run in the terminal.

```
$ cd ~/Day_2/Session_5
```

This logo will also remind you that you have work to do.

Slides with a **Gold** background: hints, solutions, or explanations.

They'll also have this logo as a reminder that we're working on a challenge.

Part 1: Stars in a Nutshell

"You'd look pretty simple from 10 parsecs away, too."

– Fred Hoyle

Periodic Table of the Elements

Created in the Big Bang

Created by stars (and their explosive deaths)

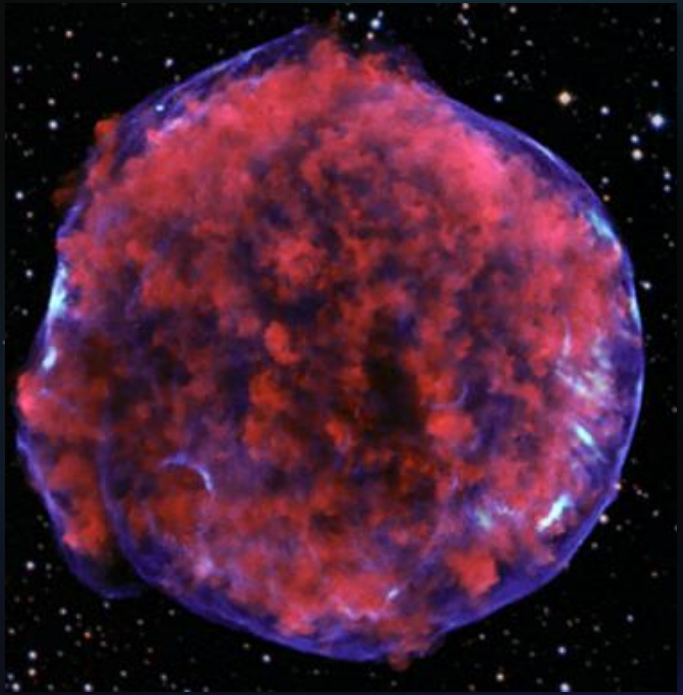
1 H Hydrogen 1.008 $1s^1$																	2 He Helium 4.003 $1s^2$
3 Li Lithium 6.941 $[He]2s^1$	4 Be Beryllium 9.012 $[He]2s^2$											5 B Boron 10.811 $[He]2s^22p^1$	6 C Carbon 12.011 $[He]2s^22p^2$	7 N Nitrogen 14.007 $[He]2s^22p^3$	8 O Oxygen 15.999 $[He]2s^22p^4$	9 F Fluorine 18.998 $[He]2s^22p^5$	10 Ne Neon 20.180 $[He]2s^22p^6$
11 Na Sodium 22.990 $[Ne]3s^1$	12 Mg Magnesium 24.305 $[Ne]3s^2$											13 Al Aluminum 26.982 $[Ne]3s^23p^1$	14 Si Silicon 28.086 $[Ne]3s^23p^2$	15 P Phosphorus 30.974 $[Ne]3s^23p^3$	16 S Sulfur 32.066 $[Ne]3s^23p^4$	17 Cl Chlorine 35.453 $[Ne]3s^23p^5$	18 Ar Argon 39.948 $[Ne]3s^23p^6$
19 K Potassium 39.098 $[Ar]4s^1$	20 Ca Calcium 40.078 $[Ar]4s^2$	21 Sc Scandium 44.956 $[Ar]3d^14s^2$	22 Ti Titanium 47.88 $[Ar]3d^24s^2$	23 V Vanadium 50.942 $[Ar]3d^34s^2$	24 Cr Chromium 51.996 $[Ar]3d^54s^1$	25 Mn Manganese 54.938 $[Ar]3d^54s^2$	26 Fe Iron 55.933 $[Ar]3d^64s^2$	27 Co Cobalt 58.933 $[Ar]3d^74s^2$	28 Ni Nickel 58.693 $[Ar]3d^84s^2$	29 Cu Copper 63.546 $[Ar]3d^{10}4s^1$	30 Zn Zinc 65.39 $[Ar]3d^{10}4s^2$	31 Ga Gallium 69.732 $[Ar]3d^{10}4s^24p^1$	32 Ge Germanium 72.61 $[Ar]3d^{10}4s^24p^2$	33 As Arsenic 74.922 $[Ar]3d^{10}4s^24p^3$	34 Se Selenium 78.972 $[Ar]3d^{10}4s^24p^4$	35 Br Bromine 79.904 $[Ar]3d^{10}4s^24p^5$	36 Kr Krypton 84.80 $[Ar]3d^{10}4s^24p^6$
37 Rb Rubidium 84.468 $[Kr]5s^1$	38 Sr Strontium 87.62 $[Kr]5s^2$	39 Y Yttrium 88.906 $[Kr]4d^15s^2$	40 Zr Zirconium 91.224 $[Kr]4d^25s^2$	41 Nb Niobium 92.906 $[Kr]4d^45s^1$	42 Mo Molybdenum 95.95 $[Kr]4d^55s^1$	43 Tc Technetium 98.907 $[Kr]4d^55s^2$	44 Ru Ruthenium 101.07 $[Kr]4d^75s^1$	45 Rh Rhodium 102.906 $[Kr]4d^85s^1$	46 Pd Palladium 106.42 $[Kr]4d^{10}$	47 Ag Silver 107.868 $[Kr]4d^{10}5s^1$	48 Cd Cadmium 112.411 $[Kr]4d^{10}5s^2$	49 In Indium 114.818 $[Kr]4d^{10}5s^25p^1$	50 Sn Tin 118.71 $[Kr]4d^{10}5s^25p^2$	51 Sb Antimony 121.760 $[Kr]4d^{10}5s^25p^3$	52 Te Tellurium 127.6 $[Kr]4d^{10}5s^25p^4$	53 I Iodine 126.904 $[Kr]4d^{10}5s^25p^5$	54 Xe Xenon 131.29 $[Kr]4d^{10}5s^25p^6$
55 Cs Cesium 132.905 $[Xe]6s^1$	56 Ba Barium 137.327 $[Xe]6s^2$	57-71	72 Hf Hafnium 178.49 $[Xe]4f^{14}5d^26s^2$	73 Ta Tantalum 180.948 $[Xe]4f^{14}5d^36s^2$	74 W Tungsten 183.85 $[Xe]4f^{14}5d^46s^2$	75 Re Rhenium 186.207 $[Xe]4f^{14}5d^56s^2$	76 Os Osmium 190.23 $[Xe]4f^{14}5d^66s^2$	77 Ir Iridium 192.22 $[Xe]4f^{14}5d^76s^2$	78 Pt Platinum 195.08 $[Xe]4f^{14}5d^96s^1$	79 Au Gold 196.967 $[Xe]4f^{14}5d^{10}6s^1$	80 Hg Mercury 200.59 $[Xe]4f^{14}5d^{10}6s^2$	81 Tl Thallium 204.383 $[Xe]4f^{14}5d^{10}6s^26p^1$	82 Pb Lead 207.2 $[Xe]4f^{14}5d^{10}6s^26p^2$	83 Bi Bismuth 208.980 $[Xe]4f^{14}5d^{10}6s^26p^3$	84 Po Polonium [208.982] $[Xe]4f^{14}5d^{10}6s^26p^4$	85 At Astatine 209.987 $[Xe]4f^{14}5d^{10}6s^26p^5$	86 Rn Radon 222.018 $[Xe]4f^{14}5d^{10}6s^26p^6$
87 Fr Francium 223.020 $[Rn]7s^1$	88 Ra Radium 226.025 $[Rn]7s^2$	89-103	104 Rf Rutherfordium [261] $[Rn]5f^{14}6d^27s^{2*}$	105 Db Dubnium [262] $[Rn]5f^{14}6d^37s^{2*}$	106 Sg Seaborgium [266] $[Rn]5f^{14}6d^47s^{2*}$	107 Bh Bohrium [264] $[Rn]5f^{14}6d^57s^{2*}$	108 Hs Hassium [269] $[Rn]5f^{14}6d^67s^{2*}$	109 Mt Meitnerium [268] $[Rn]5f^{14}6d^77s^{2*}$	110 Ds Darmstadtium [269] $[Rn]5f^{14}6d^87s^{2*}$	111 Rg Roentgenium [272] $[Rn]5f^{14}6d^97s^{2*}$	112 Cn Copernicium [277] $[Rn]5f^{14}6d^{10}7s^{2*}$	113 Uut Ununtrium unknown $[Rn]5f^{14}6d^{10}7s^27p^1$	114 Fl Flerovium [289] $[Rn]5f^{14}6d^{10}7s^27p^2$	115 Uup Ununpentium unknown $[Rn]5f^{14}6d^{10}7s^27p^3$	116 Lv Livermorium [298] $[Rn]5f^{14}6d^{10}7s^27p^4$	117 Uus Ununseptium unknown $[Rn]5f^{14}6d^{10}7s^27p^5$	118 Uuo Ununoctium unknown $[Rn]5f^{14}6d^{10}7s^27p^6$

Configurations denoted with a * are unknown and the listed values are predicted.

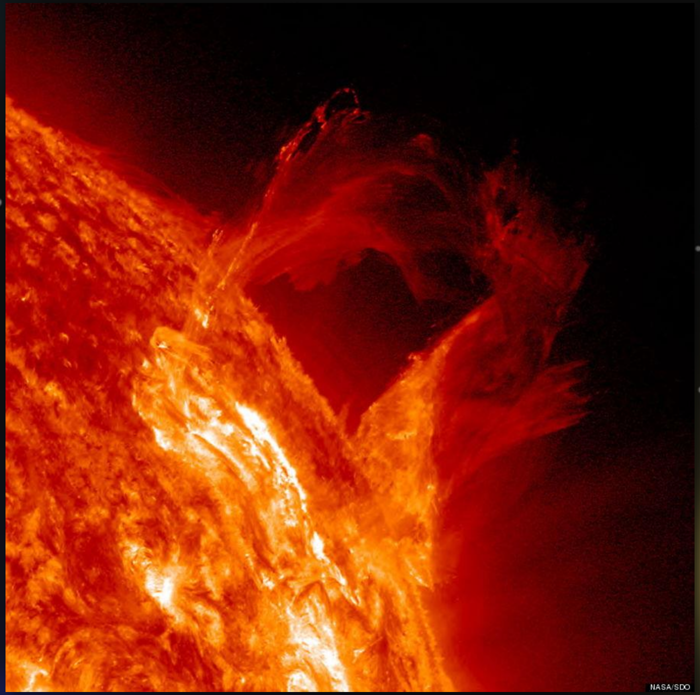
Created by the pride of humanity

57 La Lanthanum 138.906 $[Xe]5d^16s^2$	58 Ce Cerium 140.115 $[Xe]4f^15d^16s^2$	59 Pr Praseodymium 140.908 $[Xe]4f^36s^2$	60 Nd Neodymium 144.24 $[Xe]4f^46s^2$	61 Pm Promethium 144.913 $[Xe]4f^56s^2$	62 Sm Samarium 150.36 $[Xe]4f^66s^2$	63 Eu Europium 151.966 $[Xe]4f^76s^2$	64 Gd Gadolinium 157.25 $[Xe]4f^75d^16s^2$	65 Tb Terbium 158.925 $[Xe]4f^96s^2$	66 Dy Dysprosium 162.50 $[Xe]4f^{10}6s^2$	67 Ho Holmium 164.930 $[Xe]4f^{11}6s^2$	68 Er Erbium 167.26 $[Xe]4f^{12}6s^2$	69 Tm Thulium 168.934 $[Xe]4f^{13}6s^2$	70 Yb Ytterbium 173.04 $[Xe]4f^{14}6s^2$	71 Lu Lutetium 174.967 $[Xe]4f^{14}5d^16s^2$
89 Ac Actinium 227.028 $[Rn]6d^17s^2$	90 Th Thorium 232.038 $[Rn]6d^27s^2$	91 Pa Protactinium 231.036 $[Rn]5f^26d^17s^2$	92 U Uranium 238.029 $[Rn]5f^36d^17s^2$	93 Np Neptunium 237.048 $[Rn]5f^46d^17s^2$	94 Pu Plutonium 244.064 $[Rn]5f^67s^2$	95 Am Americium 243.061 $[Rn]5f^77s^2$	96 Cm Curium 247.070 $[Rn]5f^76d^17s^2$	97 Bk Berkelium 247.070 $[Rn]5f^97s^2$	98 Cf Californium 251.080 $[Rn]5f^{10}7s^2$	99 Es Einsteinium [254] $[Rn]5f^{11}7s^2$	100 Fm Fermium 257.095 $[Rn]5f^{12}7s^2$	101 Md Mendelevium 258.1 $[Rn]5f^{13}7s^2$	102 No Nobelium 259.101 $[Rn]5f^{14}7s^2$	103 Lr Lawrencium [262] $[Rn]5f^{14}6d^17s^2$

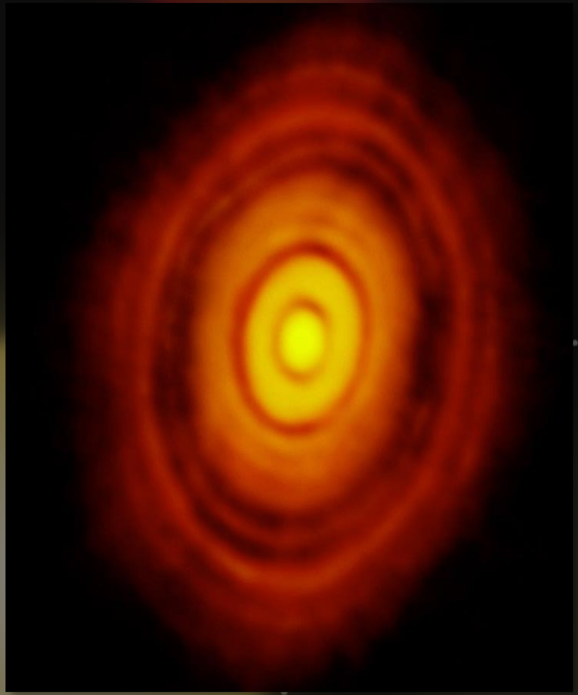
There are many reasons to study stars.



Spectacular Explosions!



Space Weather



Exoplanets

We can't visit stars (yet), so we can only study the light they emit or models of them.

MESA

***M**odules for **E**xperiments in **S**tellar **A**strophysics*

How do observers tell stars apart?

How do observers tell stars apart?

Brightness

↓

"Luminosity" (and distance)

Color

↓

"Effective Temperature"

Location

Brightness is how bright a star *appears* to be. **Luminosity** is how much energy it emits per unit time in *all* wavelengths.

This bulb has a luminosity of 5 Watts, but its brightness depends on how close you are to it.

For the sun,

$$L_\odot = 3.83 \times 10^{26} \text{ Watts}$$

We'll call this unit a **solar luminosity**.

The **effective temperature** of a hot object determines its **color**.

Cooler = Redder

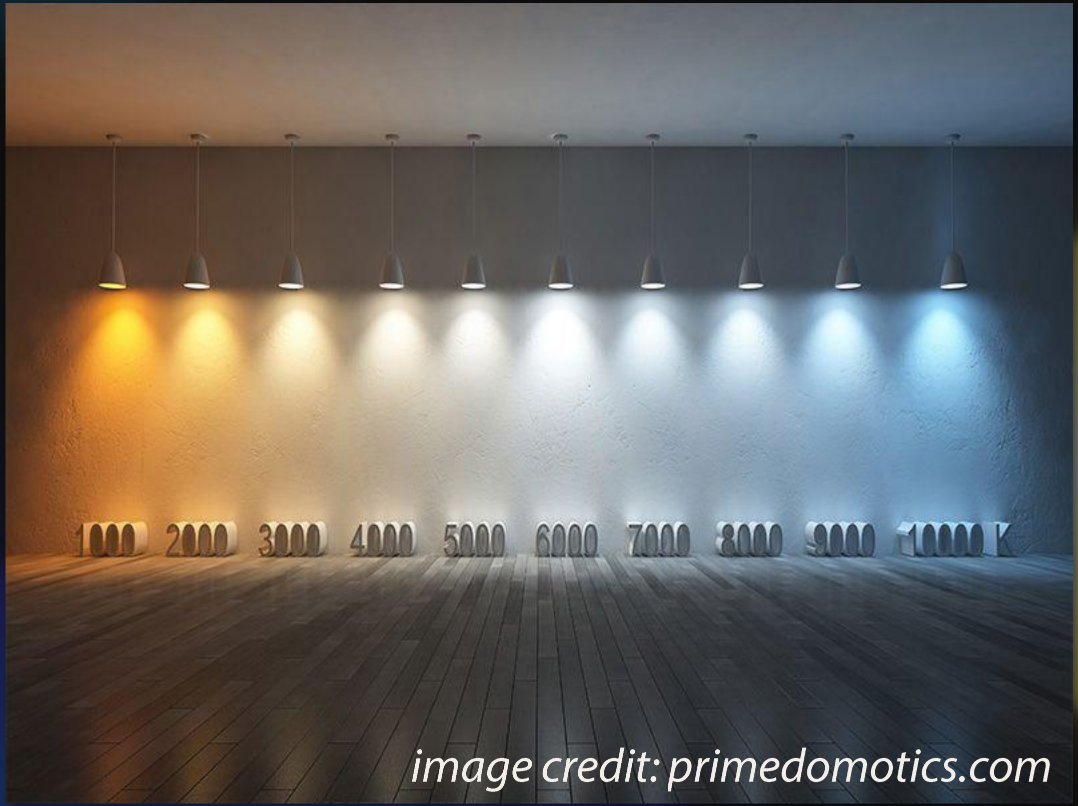


image credit: primedomotics.com

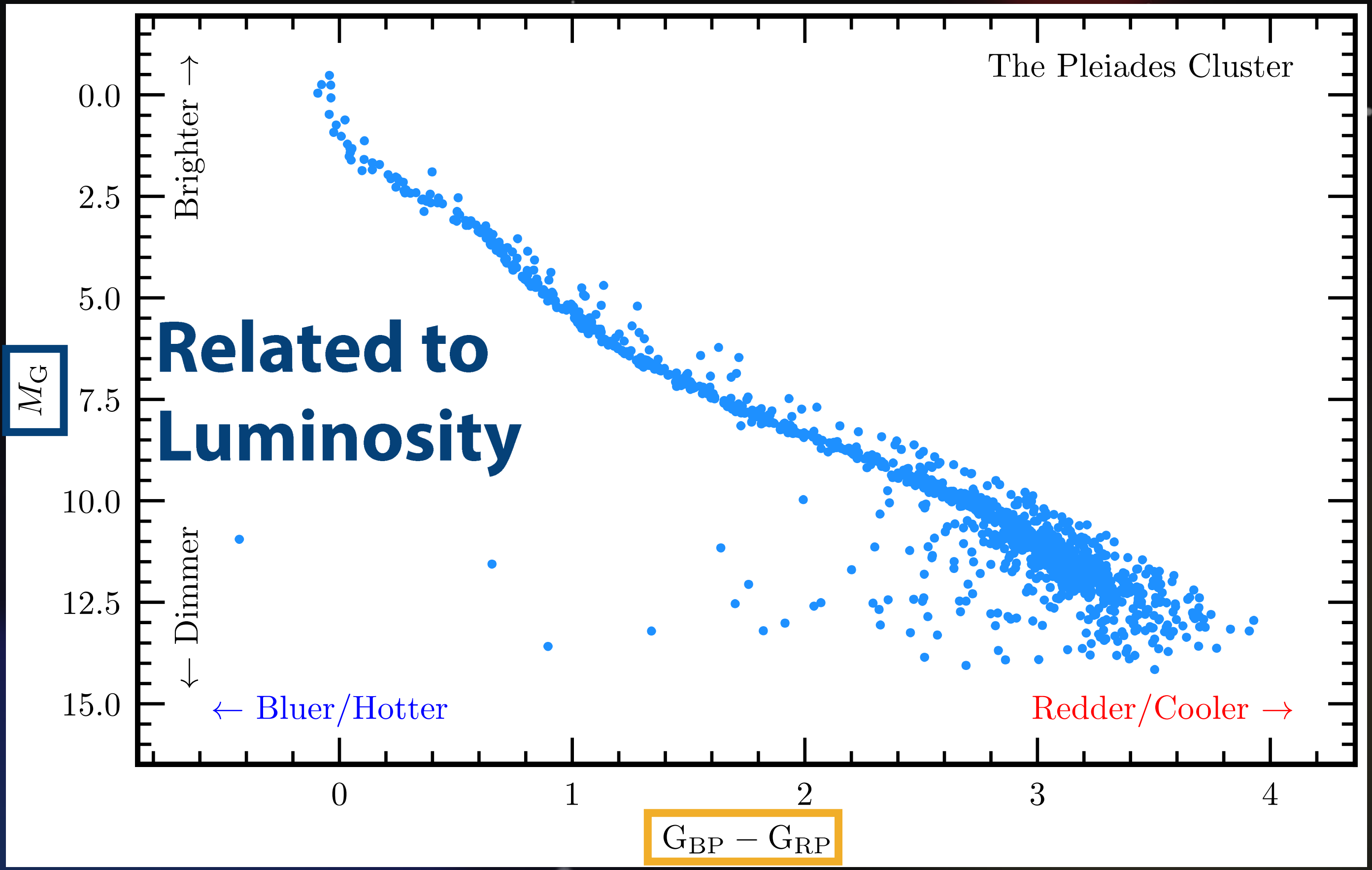
Hotter = Bluer

Stars in **clusters** have the same age and distance, but different luminosities and colors.

The Pleiades star cluster

Image credit: Raul Villaverde Fraile

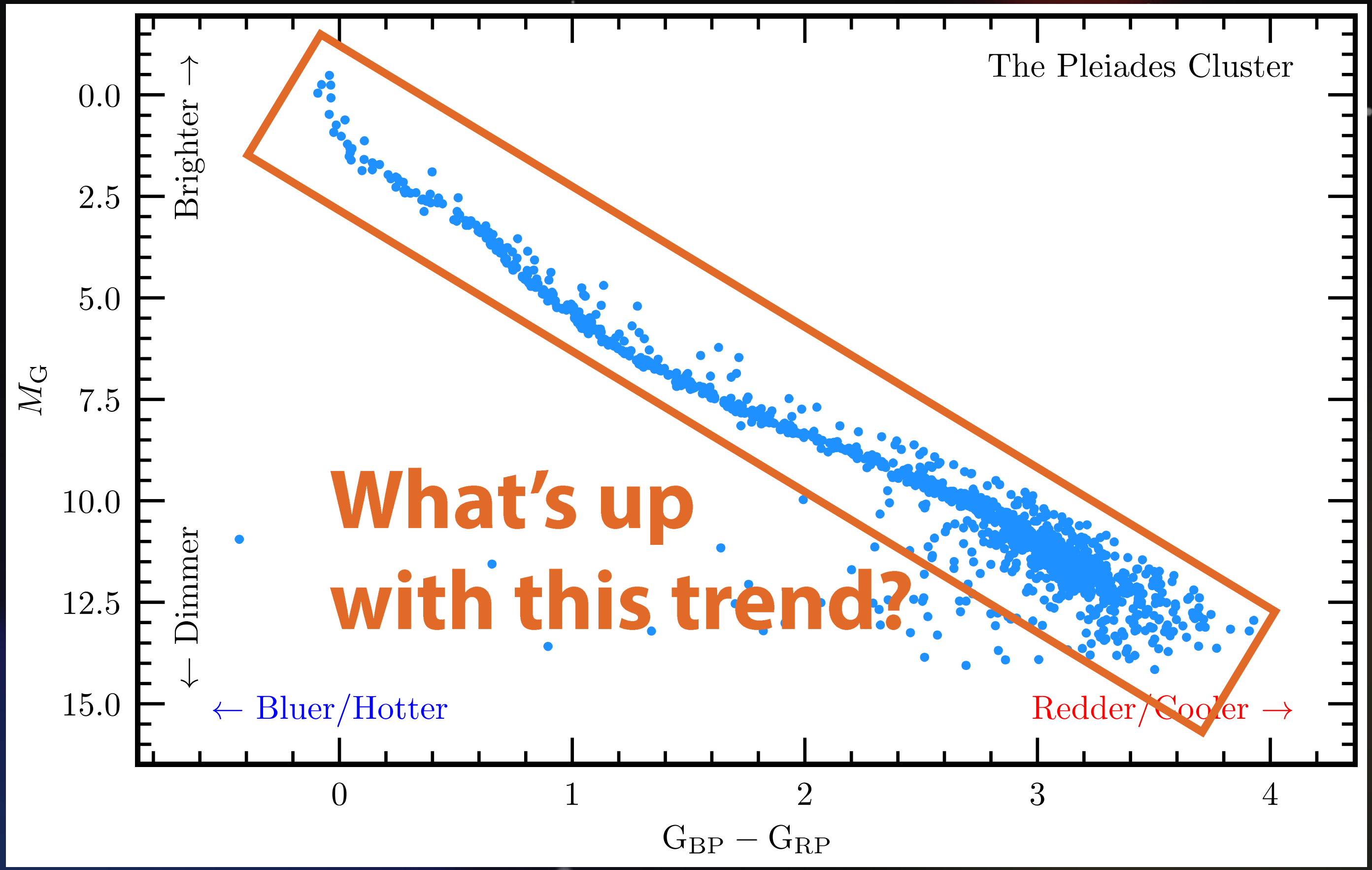
We show the luminosity/color of a stars on a **Hertzsprung-Russell (HR)** diagram.



Related to Effective Temperature

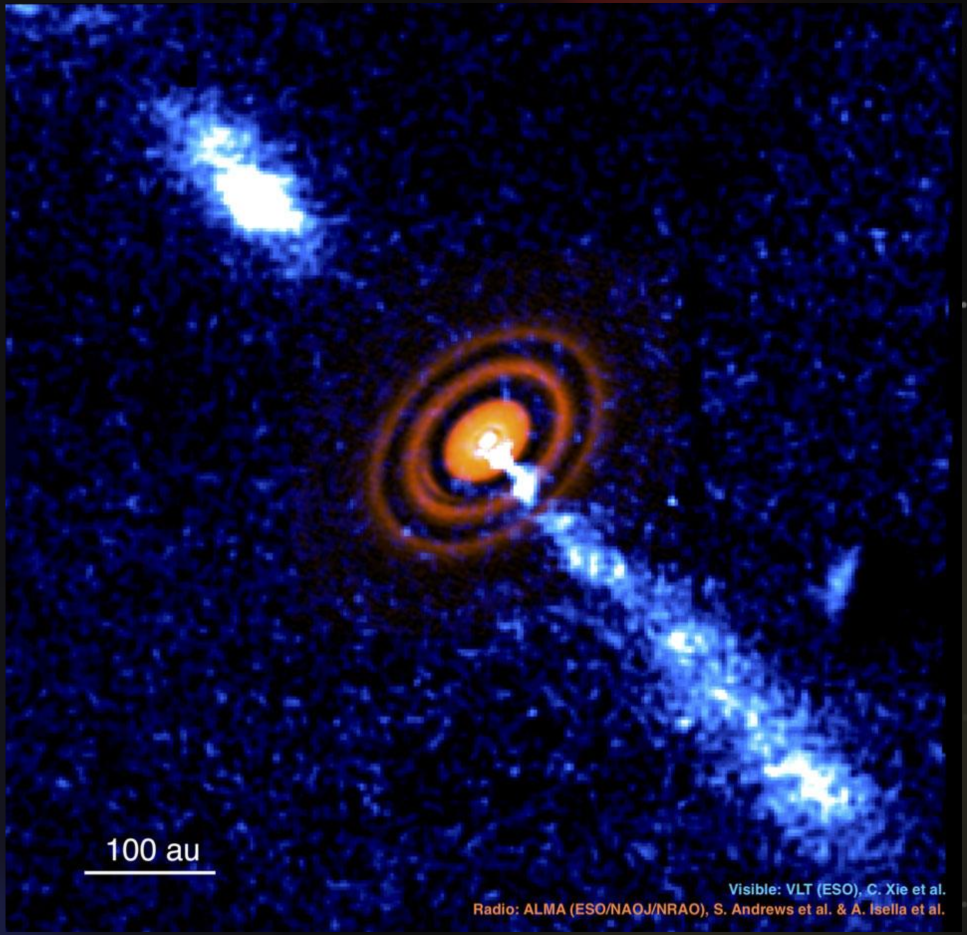
Luminosity increases along *y*-axis
Effective Temperature *decreases* along *x*-axis

We show the luminosity/color of a stars on a **Hertzsprung-Russell (HR)** diagram.

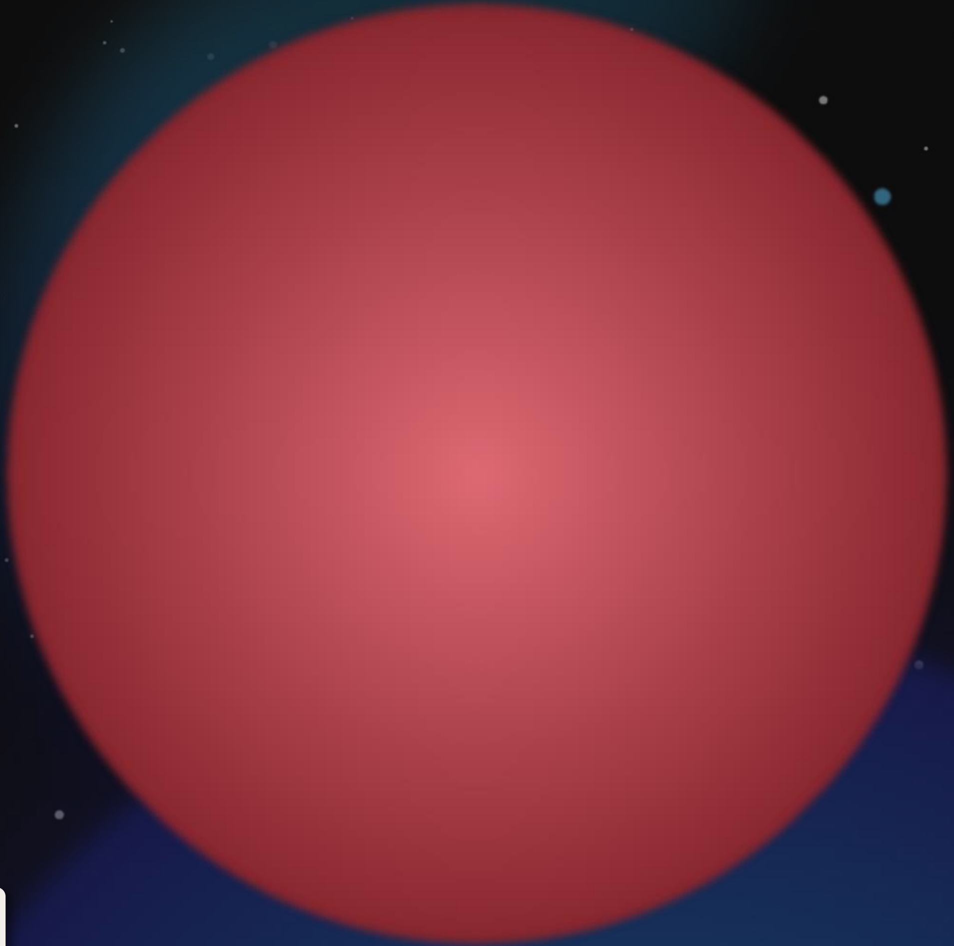


Luminosity increases along *y*-axis
Effective Temperature *decreases* along *x*-axis

Stars form when a cloud of mostly hydrogen gas and dust is compressed by its own gravity.

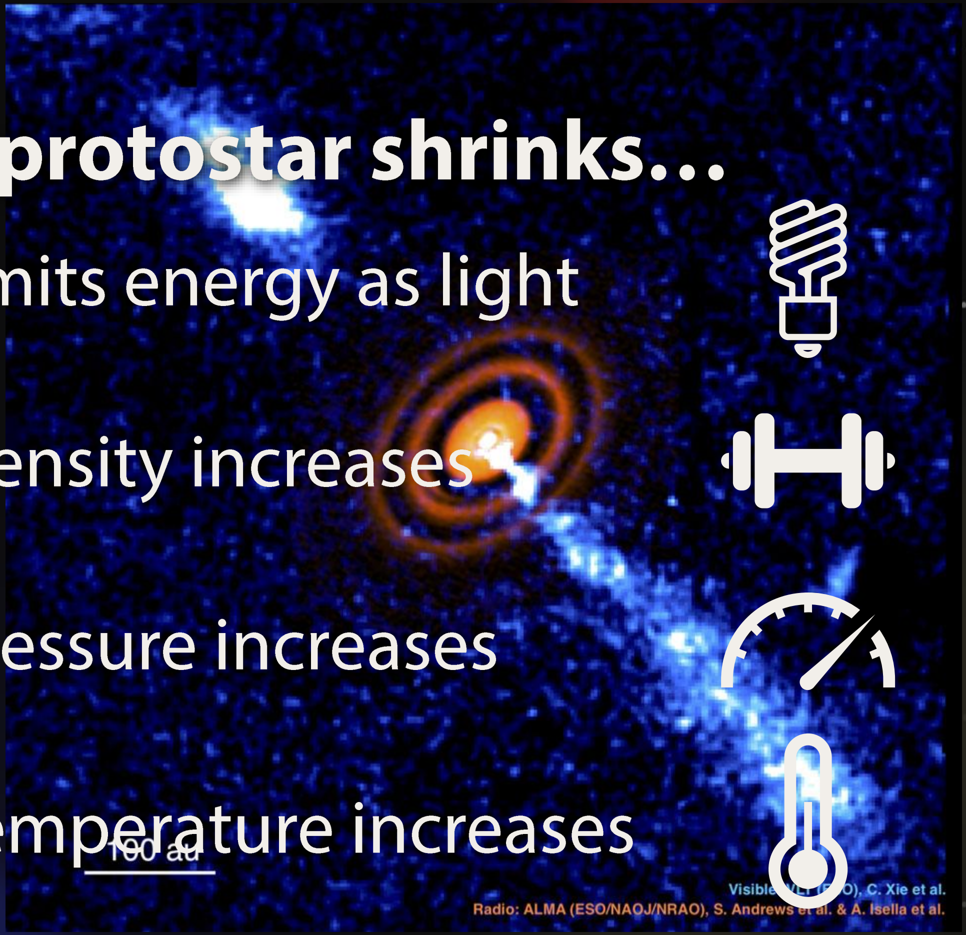


Stars form when a cloud of mostly hydrogen gas and dust is compressed by its own gravity.



As a protostar shrinks…

- Emits energy as light
- Density increases
- Pressure increases
- Temperature increases



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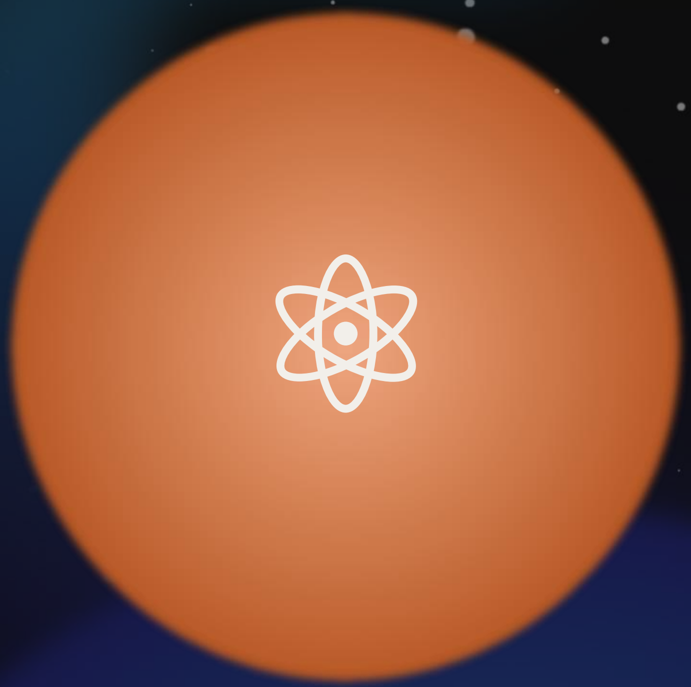
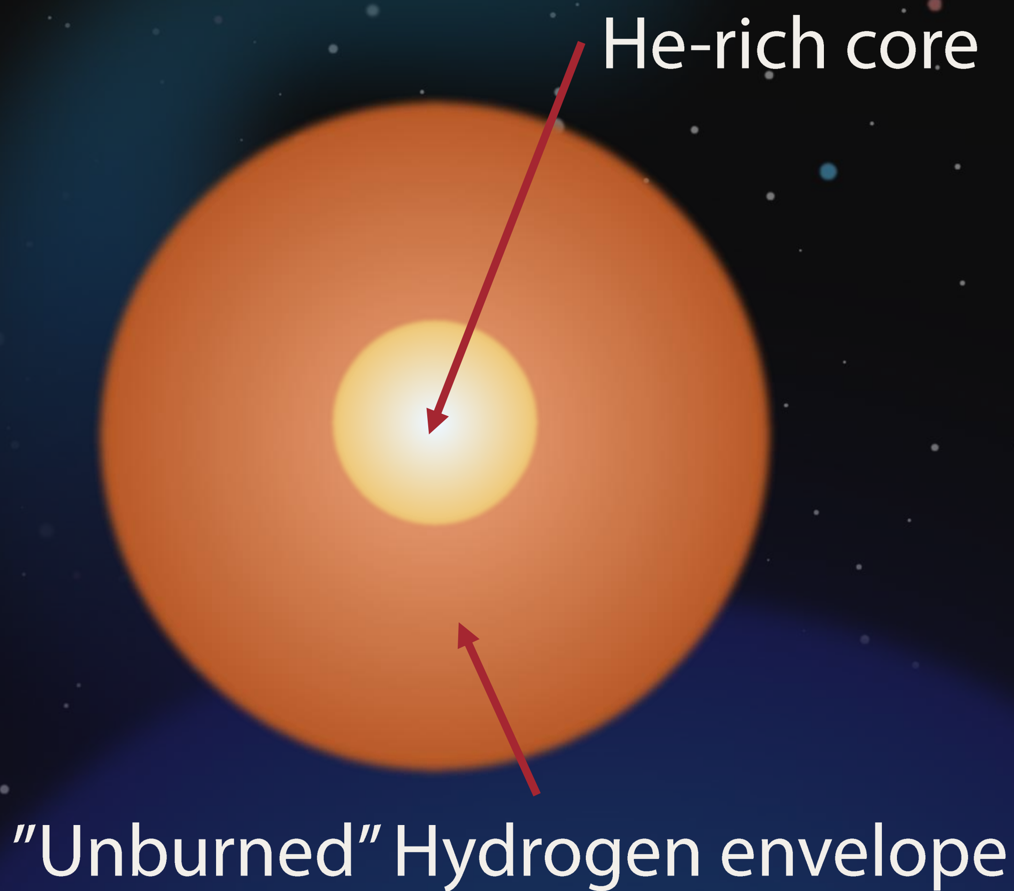


If protostar is ***massive and gets hot enough…***

It begins ***fusing hydrogen to helium*** *in its core and stops contracting*

A star is born!

While stars fuse hydrogen to helium, we say they are **main sequence** stars.



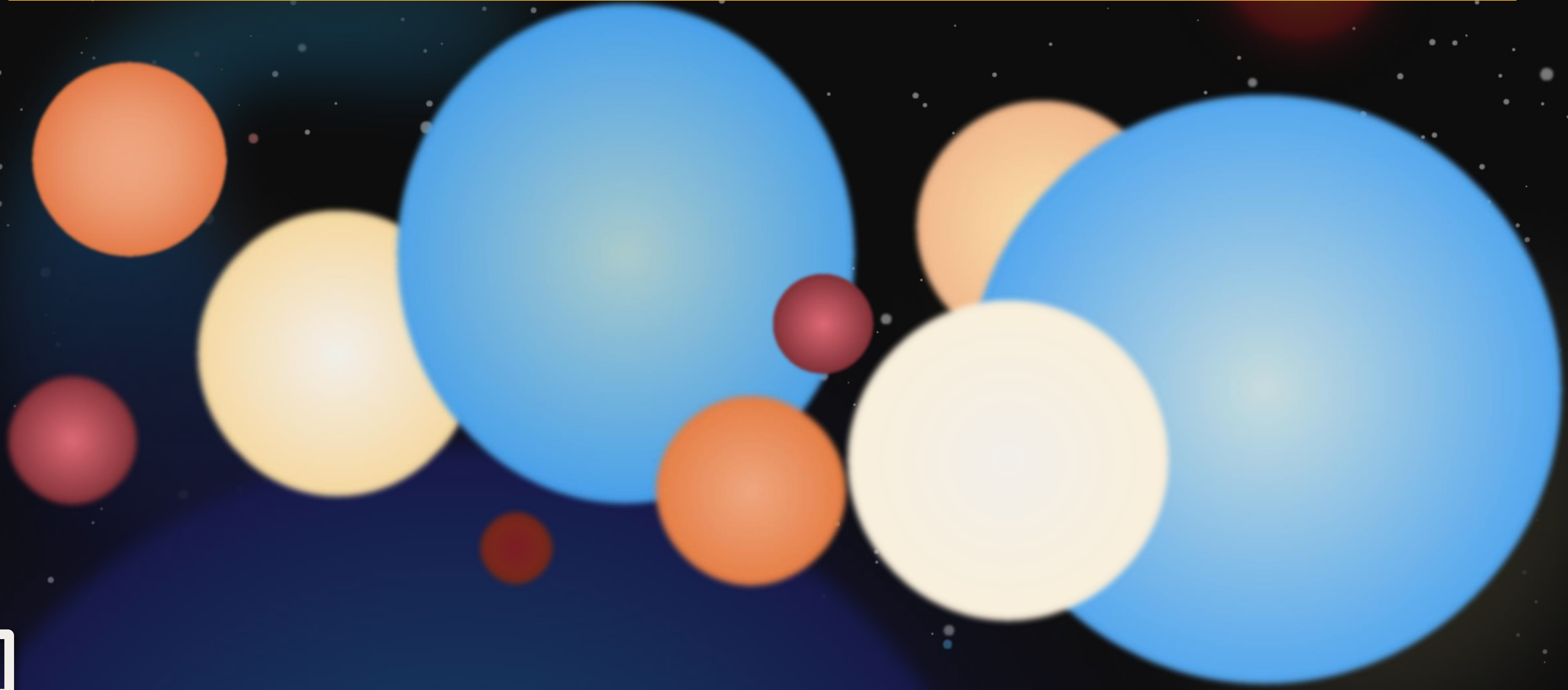
ZAMS: Zero **A**ge **M**ain **Sequence**
Newborn stars at the beginning of their main sequence lifetime

TAMS: Terminal **A**ge **M**ain **S**equence
Stars that have *just* run out of hydrogen to fuse in their cores

The sun is roughly halfway between ZAMS and TAMS

The main difference between stars in a cluster is their initial mass.

The main difference between stars in a cluster is their **initial mass**.



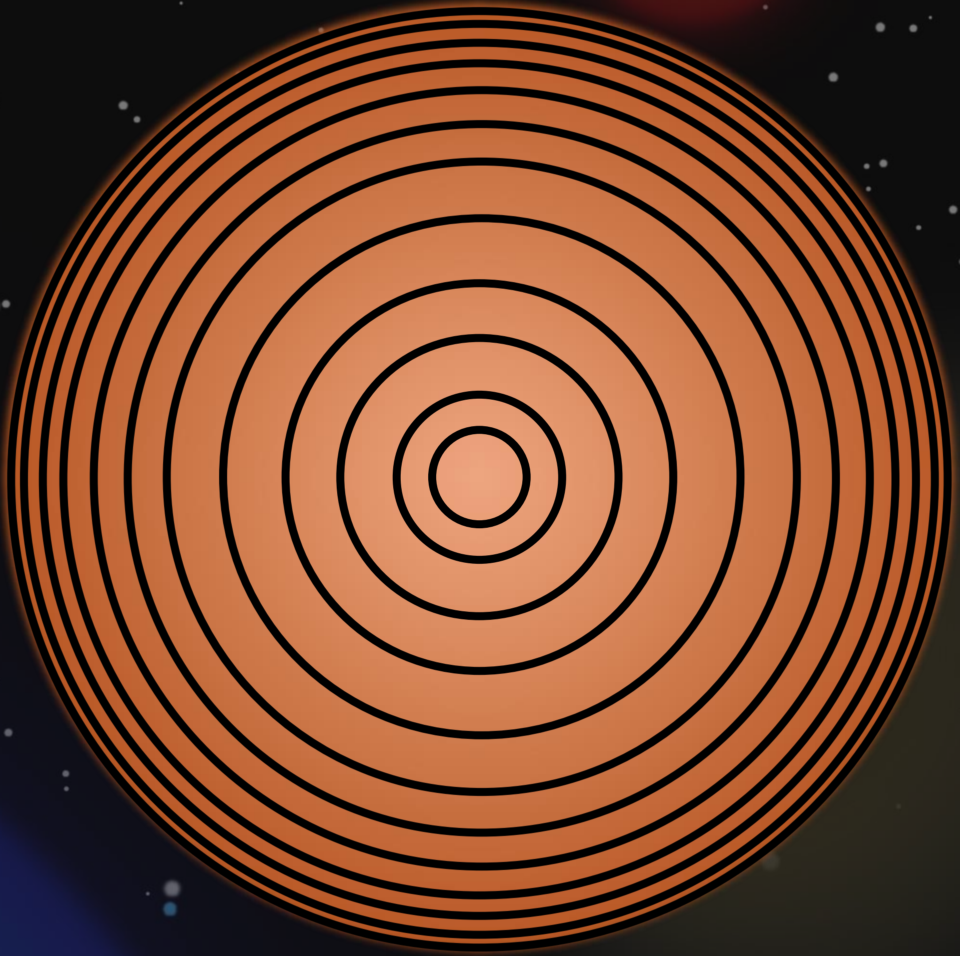
Part 2: Finding the Main Sequence

"To err is human, but to really foul things up requires a computer."

Goal: Use MESA to create stars of a **variety of masses** to reproduce the main sequence.

MESA

Modules for
Experiments in
Stellar
Astrophysics



Task 1: Get set up (if you aren't already)

A. Launch apps (use search box in lower left of screen)

- WinSCP
- PuTTY

B. Log in to bgsc on WinSCP/PuTTY (if you haven't already):

- hostname: `bgsc2.uwec.edu`
- User name (log in as)/password: last week

C. Navigate to directory:

- WinSCP: `Day_2` → `Session_5` → `to_ZAMS`
- PuTTY:

```
$ cd ~/Day_2/Session_5/to_ZAMS
```

Task 2: Set the mass of your star

A. Select your mass

- Visit this page: **https://bit.ly/hpc-stars-2022**
- Follow instructions to pick a "random" mass

B. Set mass for simulation

- Open `inlist_project` in WinSCP by double-clicking it
- Fill in the mass on the right side of the equal sign of the line that sets `initial_mass`, and then save (`Ctrl-S`) and close it

Replace "CHANGE ME" with your mass

```
! starting specifications
  initial_mass = CHANGE ME ! in Msun units
  initial_z = 0.02 ! 2% of star by mass is elements
```

Task 3: Run the Simulation

A. **Submit the job** `$ sbatch run_to_ZAMS.sh`

B. **Wait for job to complete (typically around 2 minutes)**

- You can check how it is doing by looking at the end of the `mesa.out` file `$ tail -n 20 mesa.out`
- This shows the last 20 lines of the file `mesa.out`
- Simulation is done when you see something like

```
***********************************************
* Final Luminosity             : 1.22E+05 L_sun *
* Final Effective Temperature:  39977.8 K      *
***********************************************
```

Task 4: Report Final Luminosity and Effective Temperature

A. After run is over, locate final luminosity and effective temperature from `mesa.out`

```
$ tail -n 20 mesa.out
```

B. Report data to google form (same as earlier)

`https://bit.ly/hpc-stars-2022`

- *Note*: `6.02E23` is shorthand for 6.02×10^{23} (scientific notation). Google forms understands this notation, so you can use it.

C. Check out the neat video of your simulation!

- Download `to_ZAMS.mp4` using WinSCP and watch it to see how the star evolves

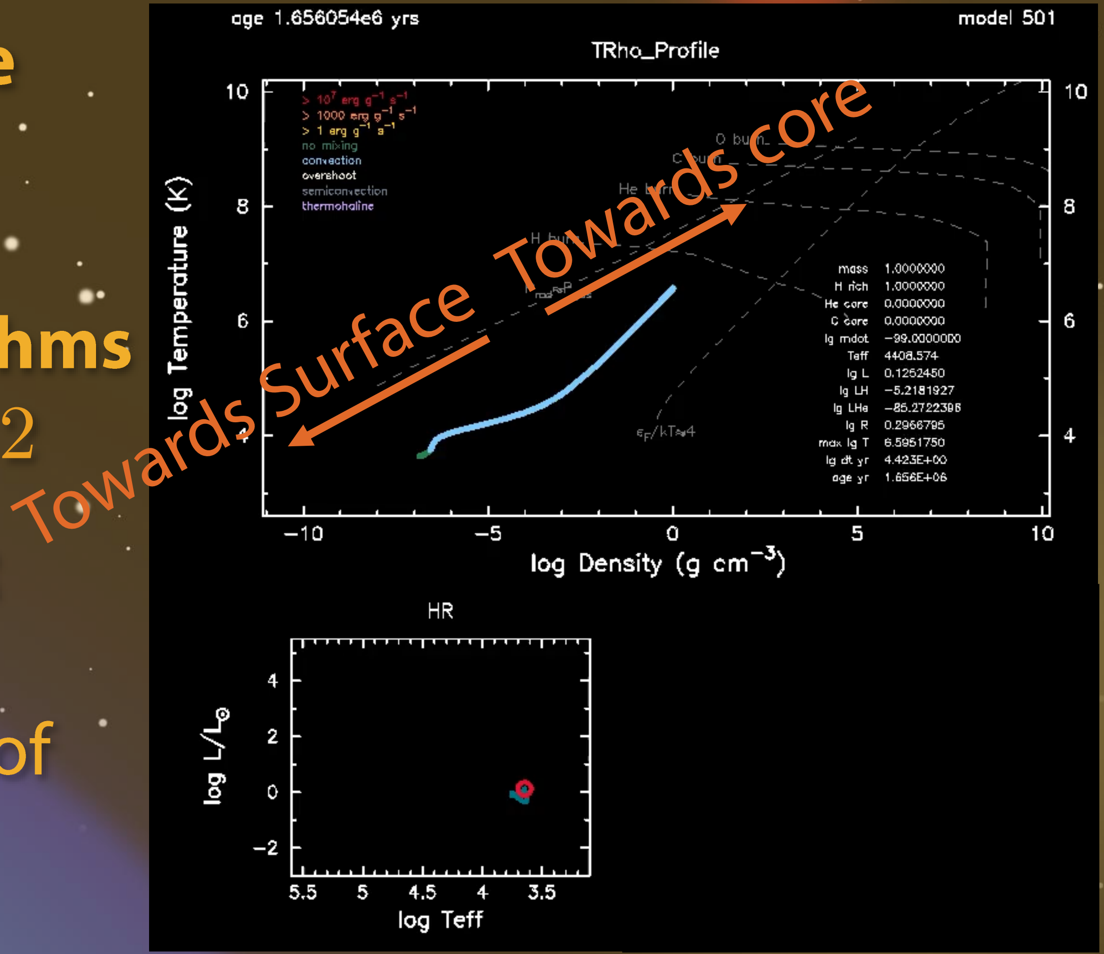
Your simulation *should* produce a video with plots showing how your stellar model is evolved.

- **Top:** Temperature vs. Density **in the stellar model**

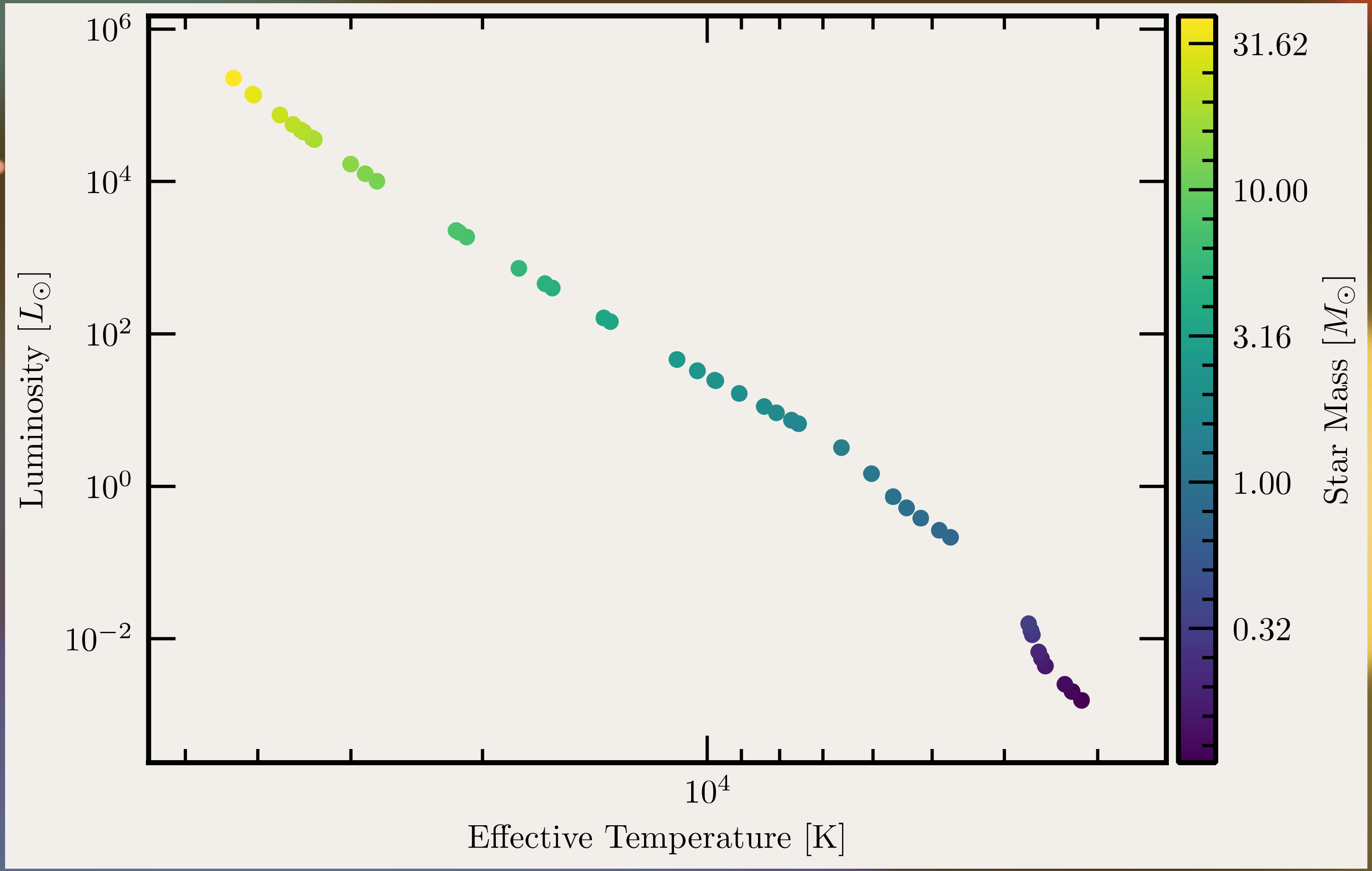
Lightning introduction to logarithms

$$100 = 10^2 \quad \Leftrightarrow \quad \log_{10}(100) = 2$$

- **Lower left:** Path of star through HR diagram. Vertical: logarithm of luminosity; horizontal: logarithm of effective temperature



Yes! The variety of masses helps explain where on the main sequence a star falls.

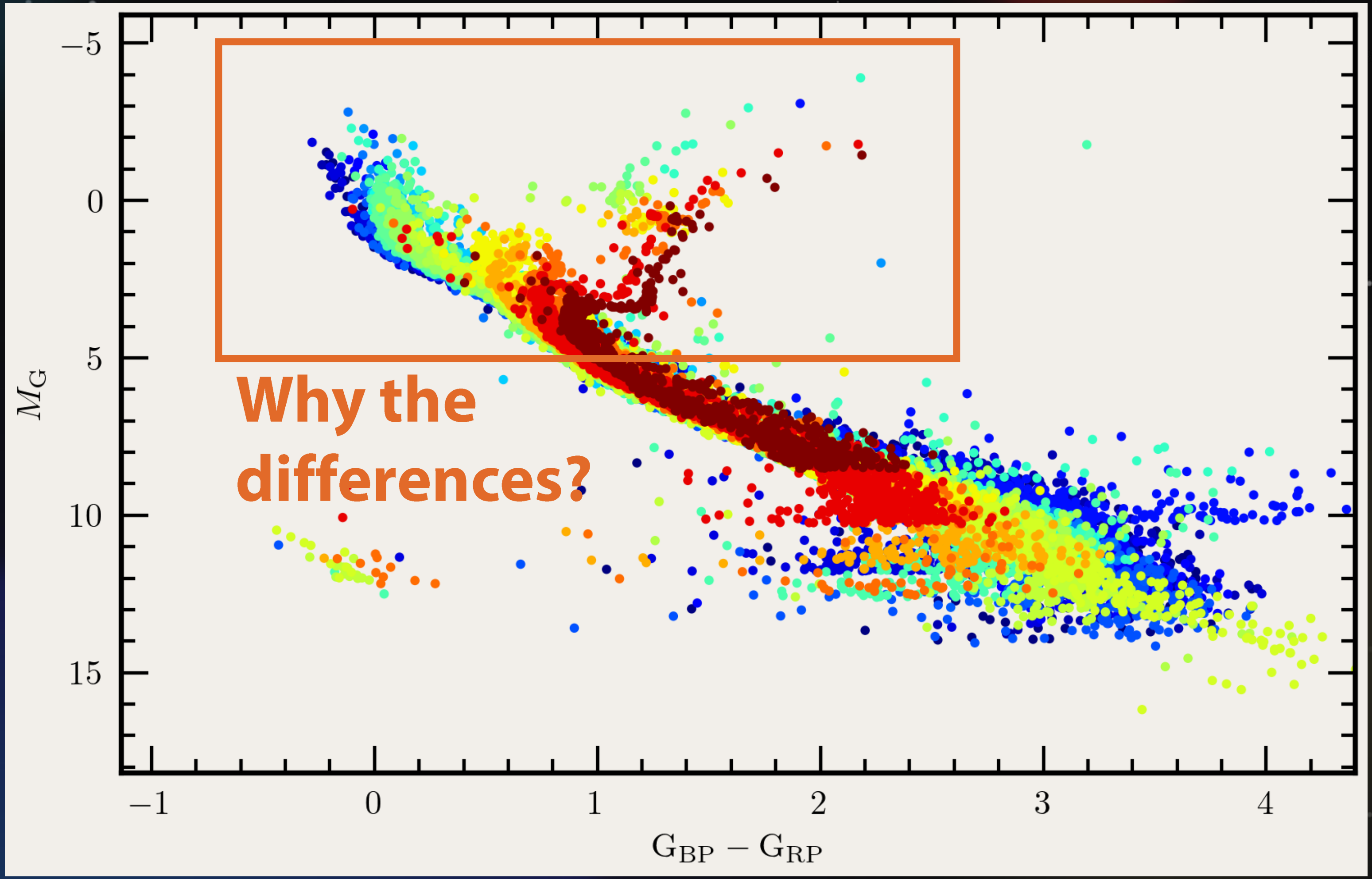


Part 3: Stellar Lifetimes

"The bigger they are, the harder they fall."

Different clusters look slightly different on the HR diagram.

- Different colors = different clusters
- Low-luminosity cutoffs due to telescope sensitivity
- High-luminosity differences… less clear



Perhaps massive stars leave main sequence more rapidly than low-mass stars?

As star runs out of hydrogen

- Core contracts
- Envelope expands

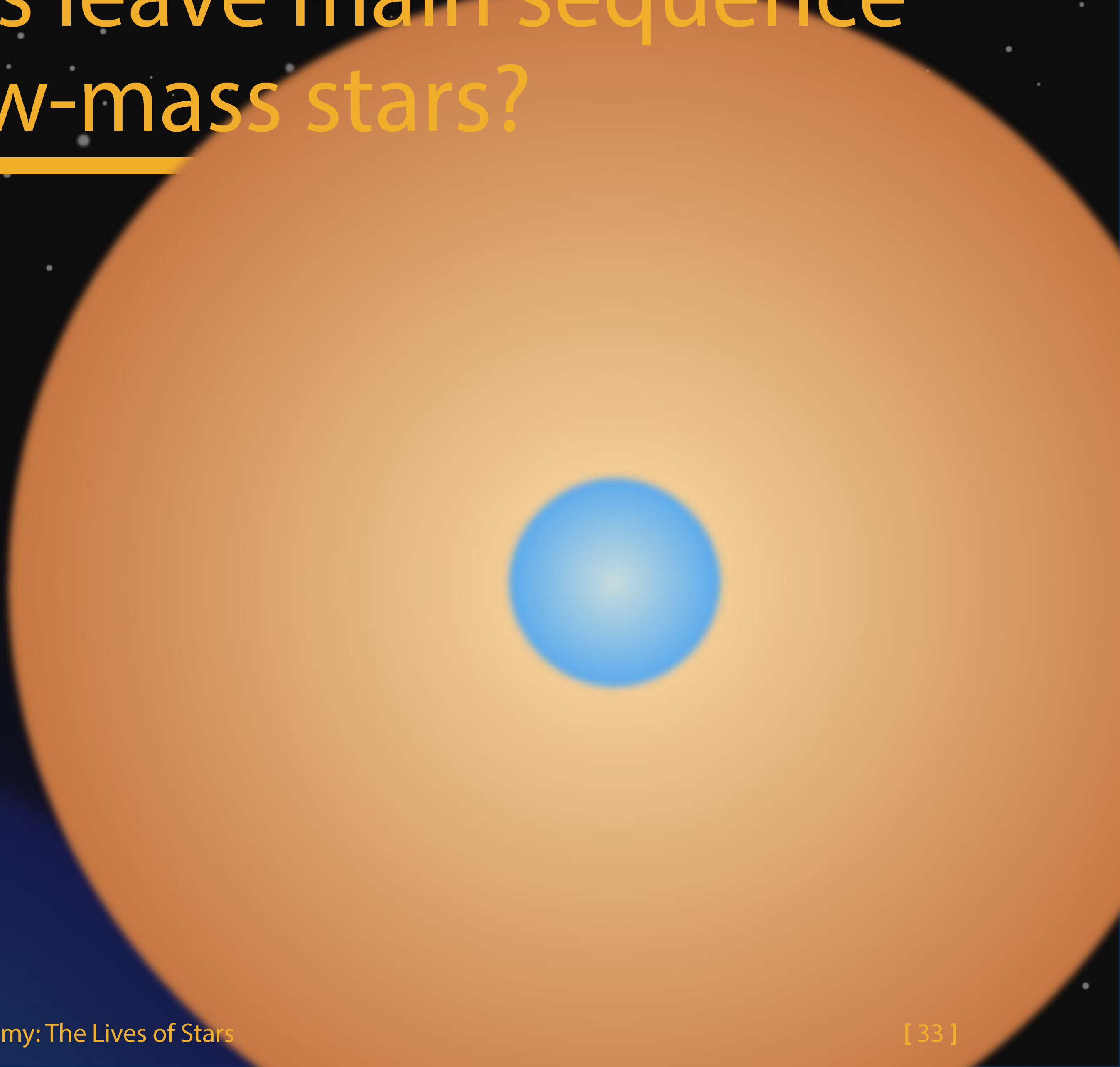
Perhaps massive stars leave main sequence more rapidly than low-mass stars?

As star runs out of hydrogen

- Core contracts
- Envelope expands

Star appears redder!

If massive stars leave main sequence first, should find a turnoff on HR diagram that varies with age



Task 5: Set up for finding Terminal Age Main Sequence (TAMS)

A. Navigate to Day_2/Session_5/to_TAMS

- WinSCP: Use dropdown menu to get back to Session_5, then open to_TAMS
- Terminal: `$ cd ~/Day_2/Session_5/to_TAMS`

B. Edit inlist_project again to set the mass to your value

- Open inlist_project in WinSCP by double-clicking it
- Fill in the mass on the right side of the equal sign of the line that sets initial_mass, and then save (Ctrl-S) and close it

Task 6: Run the Simulation

A. Submit the job `$ sbatch run_to_TAMS.sh`

B. Wait for job to complete (typically around 2 minutes)

- You can check how it is doing by looking at the end of the `mesa.out` file `$ tail -n 20 mesa.out`
- This shows the last 20 lines of the file `mesa.out`
- Simulation is done when you see something like

```
*****************************
* Final Age: 6.04E+06 years *
*****************************
```

Task 7: Report Final Age at TAMS

A. **After run is over, locate final luminosity and effective temperature from `mesa.out`**

```
$ tail -n 20 mesa.out
```

   - Final results should be surrounded by a box of asterisks near the bottom of the file
   - *Note*: this will again be in scientific notation

B. **Report mass and final age (at TAMS) on the form**

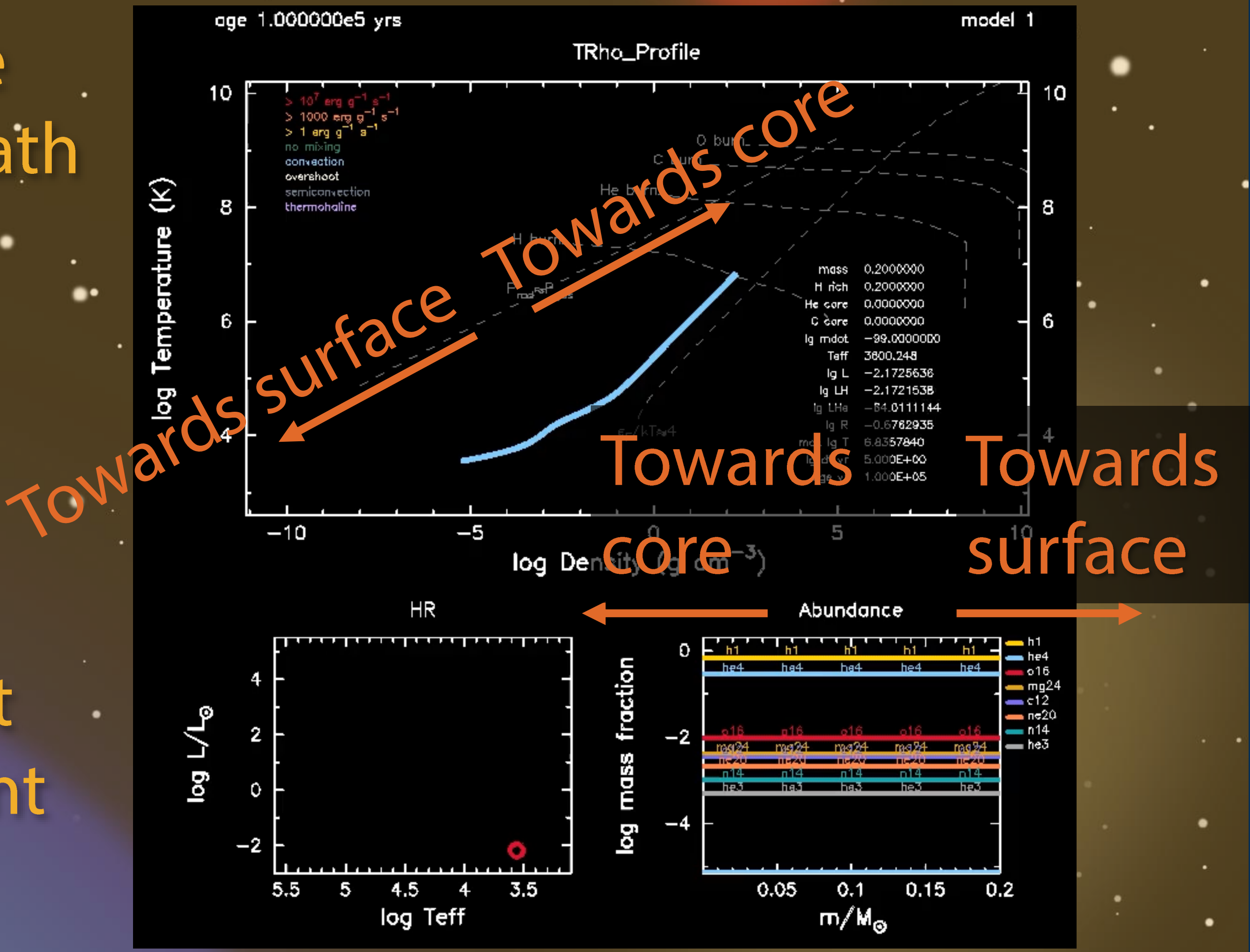
   `https://bit.ly/hpc-star-ages-2022`

   - Scientific notation is still valid. For example, 1.2E9 = 1.2×10^9

Check out to_TAMS.mp4 to see how your star evolves!

- **Top and lower left:** Same as before (temperature-density profile and path through HR diagram)

- **Lower right:** Abundance Profile
  - **x-coordinate**: how much mass is enclosed by this position
  - **y-coordinate:** fraction of matter at that location that is a given element



Yes! Massive stars live fast and die hard.

Massive stars are gas guzzlers: big tank and horrible efficiency.

Low-mass stars are the fuel-efficient cars with tiny gas tanks.

Astronomers use this **“Main Sequence Turnoff”** to estimate the age of clusters